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A SPECTROMETER FOR MEASURING THE CHARACTERISTICS OF IONS IN THE PLASMA OF THE SOLAR WIND AND THE MAGNETOSPHERE

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A SPECTROMETER FOR MEASURING THE CHARACTERISTICS OF IONS IN THE PLASMA OF THE SOLAR WIND AND THE MAGNETOSPHERE

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ABSTRACT. The principle and block diagram of instrumentation for on-board measurements of the energy spectrum of ion species H^+, He^+ and He^{++} in space are given. This ion spectrometer consists of an electrostatic analyzer and magnetic analyzer with permanent magnet. For transmitting specific ions they are accelerated or decelerated before entering the magnetic analyzer. The voltage applied corresponds to the energy step of the electrostatic analyzer and to the ion species. Open electronic multiplier is used as the ion detector. The counting rate of the secondary multiplier is measured by a logarithmic intensimeter. For a high counting rate, this is done by a current amplifier.

For lower energies the energy resolution of the instrumentation is determined by the electrostatic analyzer, at higher energies, it is determined by the magnetic analyzer. Both calculated and measured characteristics of the device are given and agree satisfactorily.

The first systematic measurements of the spectra of solar wind ions detected the existence of two components in the plasma stream which were preliminarily identified as proton and α-components [1]. Subsequent measurements with the aid of electrostatic analyzers of various types established the fact that the existence of secondary maxima in the energy spectra is a rather normal phenomenon [2, 3]. Since the electrostatic analyzer, which performs particle selection according to E/Q (E is the energy, and Q is the charge), does not differentiate particles with different m/Q, the /3*

*Numbers in the margin indicate pagination in the original foreign text.

interpretation of the spectra was made on the assumption of equality in the mass rate for the different ions in the plasma stream. Under the rare conditions of low plasma temperature, resolution of several ion components was achieved [4] (Figure 1). However, in the majority of cases in the interplanetary medium and always in the Earth's magnetosphere and in the transition region, the energy spectrum of the particles is very wide, and it does not appear to be possible to resolve the various ions in this case. The necessity for separate measurements of the energy spectra of various ion components of the plasma in space has led to attempts to produce spectrometers capable of particle selection simultaneously in electric and magnetic fields [5], or only in an electrostatic field with determination of the average charge of the particles by a double detector (particle count + collector) [6].

A combination spectrometer is described in the present paper in which, subsequent to particle analysis according to E/Q in a cylindrical electrostatic analyzer, the selection of particles according to m/Q is carried out in the field of a permanent magnet. An accelerating or decelerating potential is applied to the drift tube and the magnet, so that particles with the desired ratio m/Q acquire an energy E_m^i (more exactly, the specific impulse mv/Q) which is necessary to cross the magnetic field region and strike the exit diaphragm of the drift tube [7]. The spectrometer is intended for separate recording of proton spectra and the spectra of single-charged and double-charged He ions [8, 9].

The detecting device unit (Figure 2) includes a collimator with a system of grids, an electrostatic analyzer with a light trap, a permanent magnet with a drift tube, a system of screen grids with a diaphragm, and an ion detector.

The system of grids, which is mounted in the collimator, is intended to reflect the low-temperature plasma with a particle energy below 30 eV. The plates of the cylindrical electrostatic analyzer have a central angle

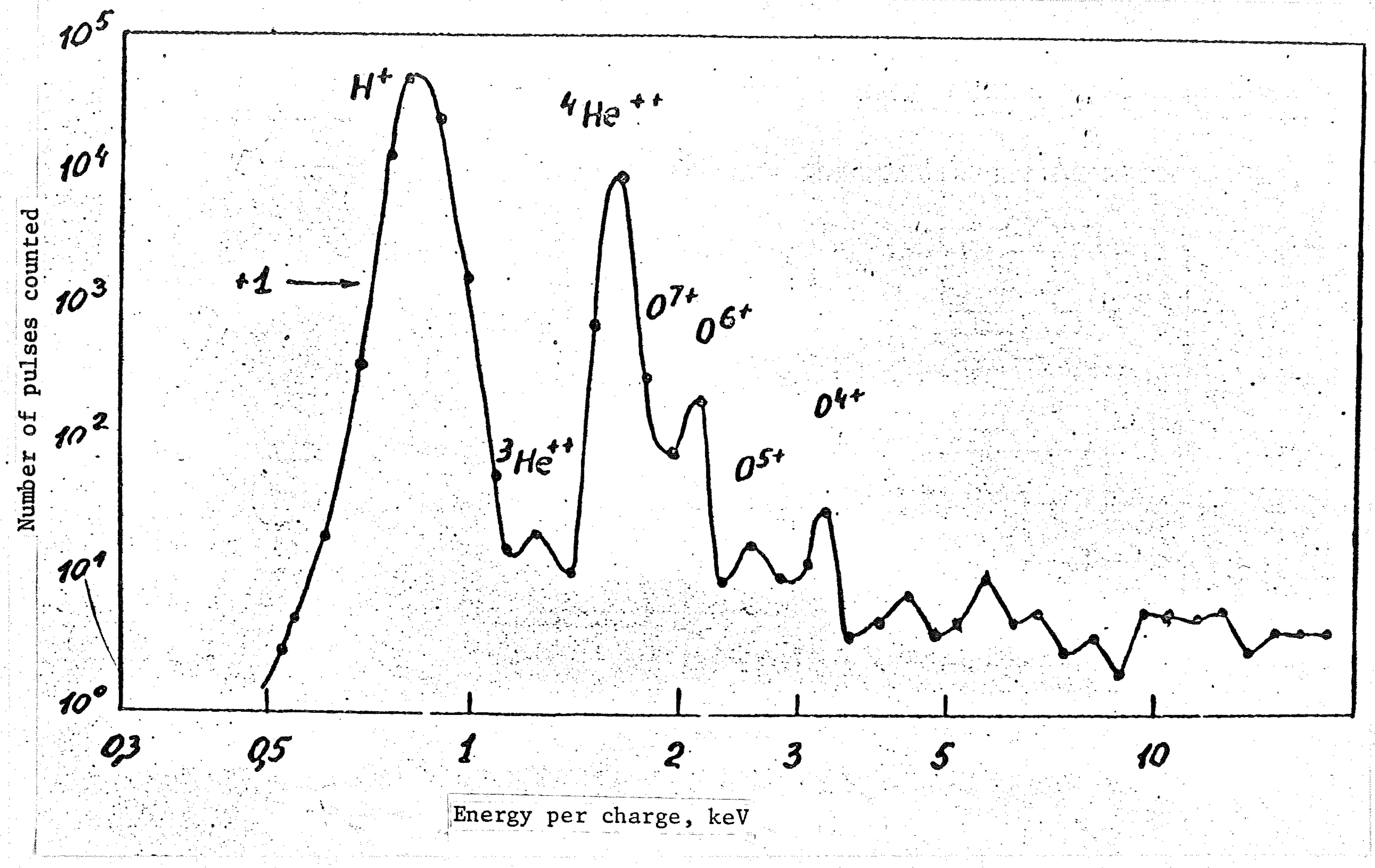

Figure 1. Typical ion spectrum in the plasma stream obtained with the aid of a quarter-spherical electrostatic analyzer [4].

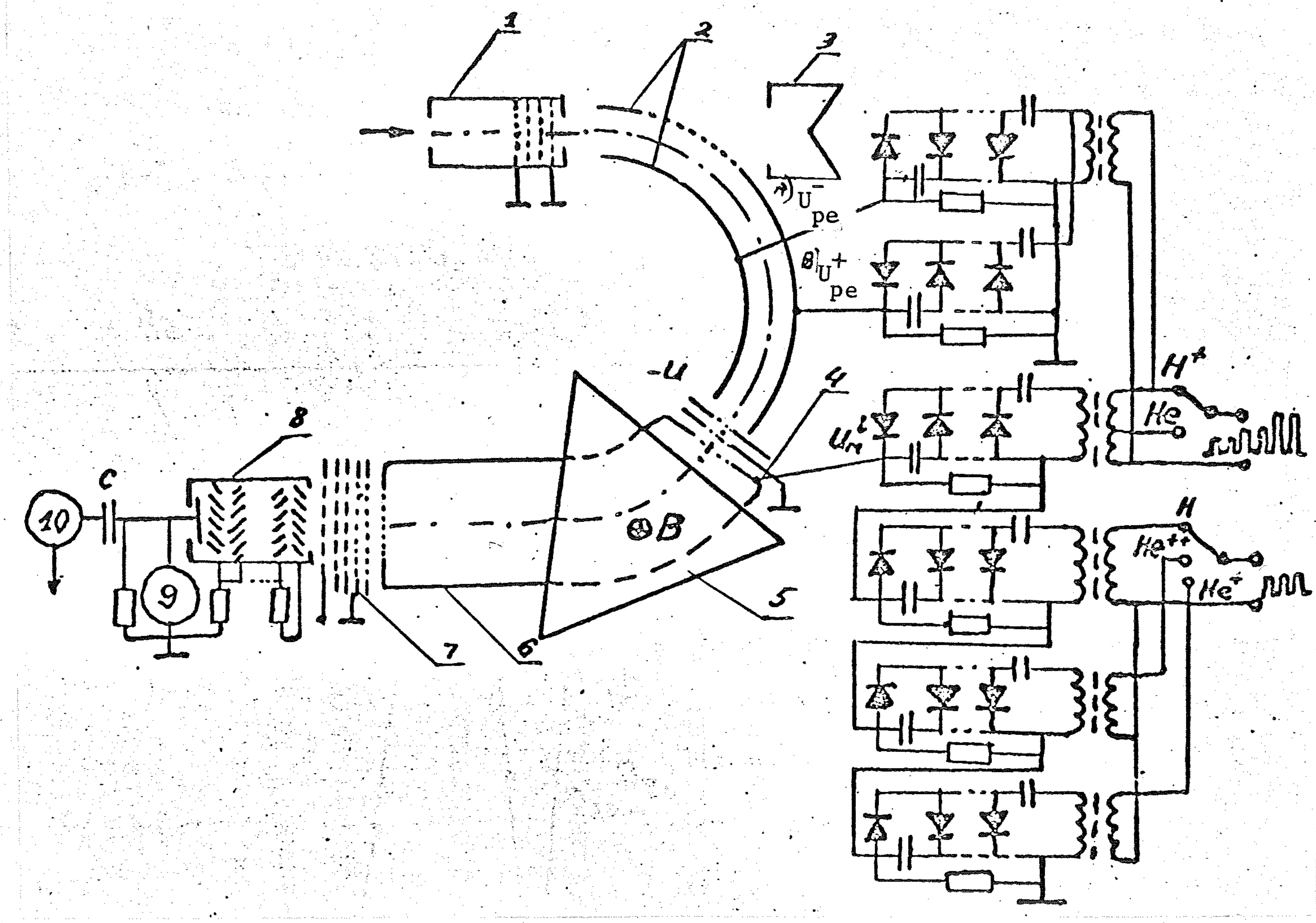

Figure 2. Structural layout of the spectrometer's detection unit: 1 - collimator, 2 - analyzer plates; 3 - light trap; 4 - diaphragm; 5 - magnet; 6 - drift tube; 7 - screen grids; 8 - secondary electron multiplier (SEM); 9 - constant-current amplifier; 10 - recorder of pulses from the SEM.

of 127°. The plates are covered with black gold in order to decrease the influence of ultraviolet radiation on the detector. The outer plate is made partly of a grid to transmit the major fraction of the radiation into the light trap.

A uniform transverse magnetic field is produced in the spectrometer by a permanent sector magnet in which the field intensity in the gap amounts to about 1300 gauss. The application of a permanent magnet and a drift tube instead of an electromagnet is a result of the need to lower the required power. For the selected radius of revolution of the particles in the magnet (R_0 = 6 cm), and under the condition of particle incidence on the detector's entrance window, the energy of protons, α-particles, and single-charged helium ions, E_m^i should be 3.0, 3.0, and 0.75 keV, respectively. An accelerating or decelerating potential, which is a function of the energy of the ions to be selected and their m/Q, is applied to the drift tube, whose entrance and exit windows are fabricated of a grid with a high degree of transmissivity. Thus, particles with an energy less than E_m^i acquire a supplementary energy, and particles with an energy greater than E_m^i are decelerated, and acquire an energy close to E_m^i. A change in the spectrometer operational conditions from recording the spectra of ions of one type to those of another type is accomplished by switching the sources which supply the plates of the electrostatic analyzer and the drift tube.

Particles with an equilibrium trajectory in the analyzer enter and exit from the magnetic field along the normal to the poles' boundary. The location of the detector is selected according to Barber's focusing rule.

A VEU-1B secondary electron multiplier (SEM) with the first two dynodes gold-plated to increase the stability and uniformity of the surface work /5
function is used in the spectrometer as the ion detector [10]. A multiplier supply voltage of u_n = -4.1 kilovolts is applied to the first dynode, and the anode is connected to the common busbar through a load resistor in order

to increase the efficiency of recording ions to 50-60%. A system of grids is set up in front of the detector to screen it from the drift tube's electric field.

The use of protective measures against ultraviolet radiation in the cylindrical analyzer and the drift tube, in combination with a general rotation of the ion beam in the spectrometer by 180°, weakened the ultraviolet radiation (according to measurements with the aid of a PRK-4 mercury-quartz lamp) by more than ten orders of magnitude. For this reason, the spectrometer is able to operate with the direction of its entrance window's axis aimed directly at the Sun [11].

The circuit for sampling signals for the detector is constructed on the principle of pulse current (charge) amplification. Recording of the signals is carried out by a logarithmic average pulse-rate meter (N = 10-100,000 pulses /sec). In addition, a constant-current amplifier, whose measurement range partially overlaps the measurement range of the rate meter, is connected simultaneously with the pulse rate recorder to the anode of the secondary electron multiplier. Both recorders provide a measurement of the frequency of signals entering from the detector in the range of 10 to 5×10^6 pulses/sec.

The energy resolution and the angle of view of the electrostatic analyzer in the plane perpendicular to the plane of the plates are determined by the collimator and are about 8.5% and 5°, respectively. The energy resolution ε' of the electrostatic analyzer for a wide particle beam is determined by the relationship $\mathcal{E}' = \frac{\Delta E_{1/2}}{E} \simeq \frac{d}{R_0}$. Since the ion energy Em in the magnet, because of deceleration or acceleration, is adjusted to be independent of the energy of the incident ions (for ions of a given kind), the energy resolution at the entrance of the magnetic selector will be equal to $\frac{\Delta E_{1/2}}{E_m'}$ for ions of a given type. Incidence of the ions on the entrance window of the secondary electron multiplier is a necessary condition for recording the ions which pass through the magnet. It is possible to obtain the limitation imposed by the magnetic selector on the width of the transmitted ion energy range if one knows the width (diameter) of the secondary electron multiplier's window and the radius $R_M 0$ of an ion's equilibrium trajectory in the magnet. Taking into account the fact that the particles are focused at the secondary electron multiplier's entrance window, we used the well-known relations $\frac{\Delta E_M}{E_M} = \frac{2\Delta V}{V}$ and $\frac{\Delta V}{V} \simeq \frac{D}{R_M^0}$, from which we obtain: $\frac{\Delta E_M}{2E_M^i} = \frac{D}{R_M^0}$. /6

Since ΔE upon entrance into the magnet is determined by the electrostatic analyzer, the condition for the secondary electron multiplier to record the ions when the entire beam, having passed through the electrostatic analyzer, is incident upon the detector's entrance window, is found from the expression: $\frac{E_0}{E_M^i} \cdot \frac{d}{R_0} \leq \frac{D}{R_M^0}$. If, upon an increase in the energy of recorded ions, a part of the ions is scattered in the magnet and is not incident on the detector's entrance window, the total energy resolution ε of the device will be lowered because of a decrease in the total sensitivity. Thus, the dependence of the device's energy resolution on the energy has two parts: the region from E_{min} to E_{lim}, where $\varepsilon = \frac{\Delta E_{1/2}}{E_0} = const.$

$$\varepsilon = \frac{\Delta E_M}{2E_0} = \frac{E_M^i}{E_0} \cdot \frac{D}{R_M^0}.$$

The dependence of the energy resolution on the energy of the recorded particles obtained for single-charged ions of helium is presented in Figure 3. It is obvious from the graph that the experimental and calculated dependencies of the energy resolution for D = 2 cm, E_M^0 = 6 cm, and $E_M^{He^+}$ = 0.64 keV agree with one another well enough.

The relation between the deflecting voltage and the ion energy for the selected radii of the plates of the electrostatic analyzer (5.55 and 6.45 cm) is $U_{pl}^{\pm} = \frac{\Delta R}{R_0} \cdot \frac{E}{Q} = 0{,}15 \frac{E}{Q}$, where ΔR is the gap between the plates, and R is the radius of an equilibrium trajectory. The limiting values of the energies of the particles recorded are E_{min} = 0.15 keV and E_{max} = 4.0 keV for protons, E_{min} = 0.6 keV and E_{max} = 16 keV for He^{++} ions, and E_{min} = 0.6 keV and E_{max} = 8 keV for He^+ ions.

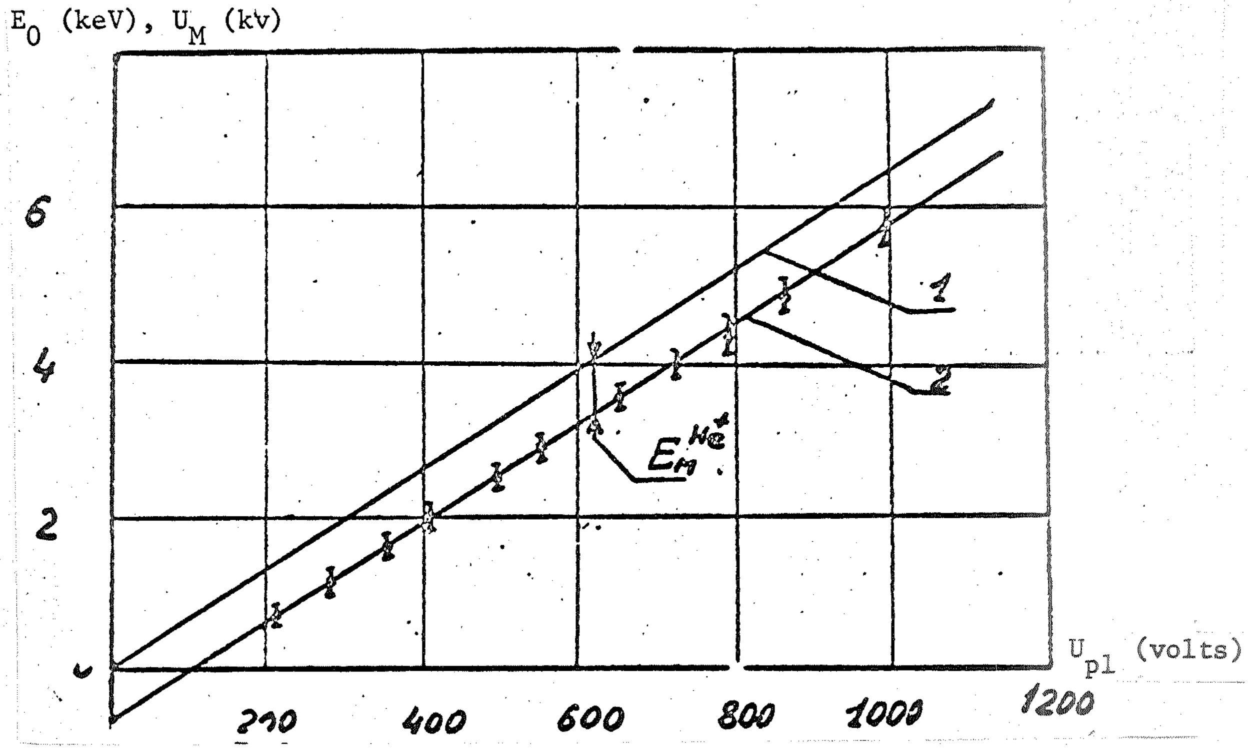

Figure 3. Energy resolution of the device:
1 - experiment; 2 - calculated dependence for He^+ ions.

A program of measurements by the spectrometer consists of the following temporal cycles of spectral distribution measurements for protons, He^{++} ions, protons, He^+ ions, and so on. Measurements every sixteen degrees (steps) are carried out in each measurement cycle. The value of a single degree on the energy scale amounts to 0.24 keV for protons, ∿1 keV for He^{++} ions, and $E_{\pi x} \simeq 0.46$ keV for He^+ ions. Shifting the operating conditions of the device from one step to the next is accomplished with the aid of external synchronizing pulses with a frequency of $f \leq 1\ sec^{-1}$. Indication of the step number and the measurement cycle ia accomplished from voltage pulses in the form of a square wave with a frequency f in recording protons, 1/2 f in recording He^+ ions, and 1/4 f in recording He^{++} ions. /7

In the case of normal incidence of a wide particle beam, the range of measurable particle fluxes is determined by the area of the collimator's entrance window (0.51 x 1.20 cm) and the multiplier's recording efficiency. In addition, a decrease in the ion recording efficiency occurs for high-energy ions as a result of defocusing of the beam at the entrance to the drift tube and in the magnet.

The measurement range for the selected entrance window area S and recording efficiency μ can be determined from the expression $\Phi = \frac{N}{S\Omega\mu\eta}$, where Φ is the flux density in particles/sec$\cdot$cm^2; Ω is the device's solid angle; N is the measured frequency from the detector in pulses/sec; and η is the transmission factor of the analyzing system from the entrance window to the detector. Thus, for $S = 0.61$ cm^2, $\Omega \simeq 7 \times 10^{-3}$ sterad, $\mu \simeq 0.55$, $\eta \simeq 0.5$, and the indicated range of frequencies to be recorded, the measurement range based on the spectrometer flux density lies within the limits from 8×10^3 to 4×10^9 particles/sec$\cdot$cm$^2\cdot$sterad at the device energy window.

Coupling of the voltages on the deflecting plates and the drift tube was one of the main difficulties in adjustment of the spectrometer. The dependencies of the frequency of the detector signals on the drift tube voltage were measured experimentally for each value of the voltage on the deflecting plates to increase the installation accuracy, and only then was the final setting of voltages carried out (Figure 4).

In conclusion, it should be noted that upon appropriate adjustments the spectrometer can be used for recording heavier ions.

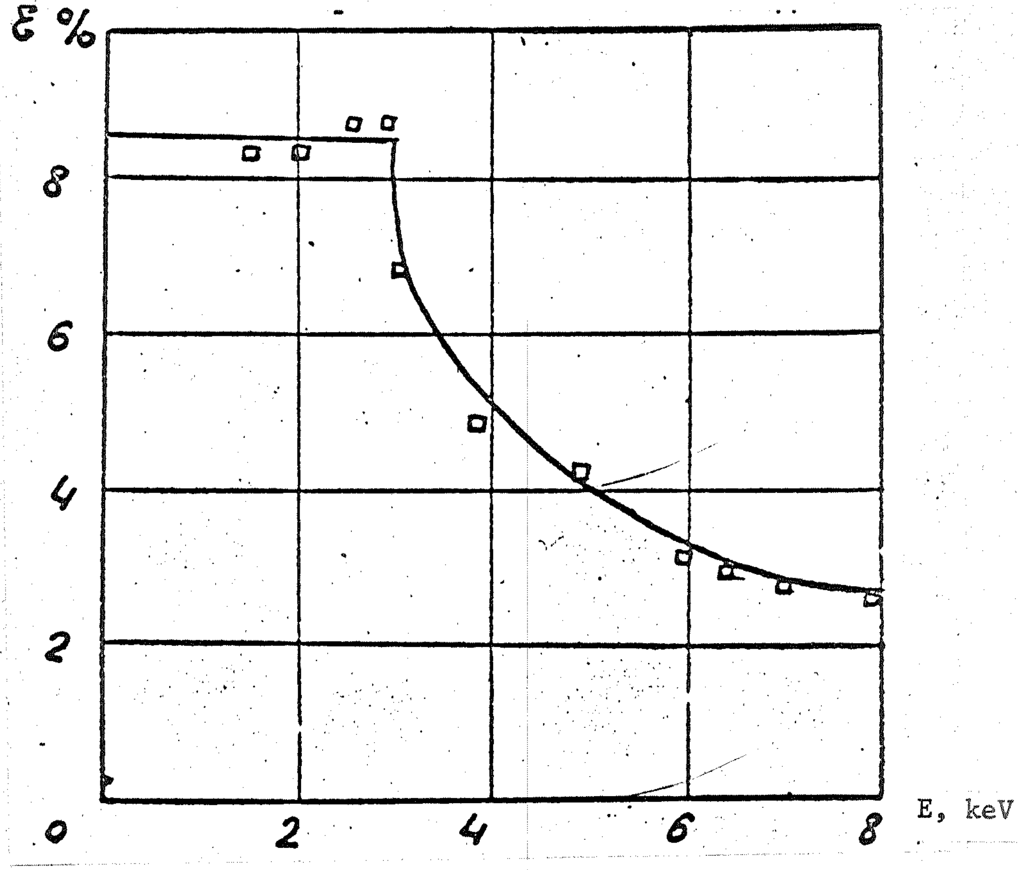

Figure 4. Energy response of the spectrometer for He^+ ions; 1 - device's energy response $\mathcal{E} = f(U_{nA}^{\pm})$ V_{re}; 2 - $U_M^{He^+} = f(V_{re}^{\pm})$ dependence.

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